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TITLE

"Noise Reduction Apparatus"

FIELD OF THE INVENTION

This invention relates to a noise reduction apparatus. The invention has particular, although not exclusive, utility in relation to use in cabins of heavy mining vehicles, where low frequency noise can present an occupational hazard. The invention can also be used in areas where noise is considered undesirable, such as marine vessels.

BACKGROUND ART

Most prior noise reduction systems for cabins have employed a feed-forward control system using a filtered-x least mean square (LMS) algorithm. One such system is disclosed in US patent specification 5,245,664. Whilst providing an adaptive controller, the conventional filtered-x LMS controller is known to have a slow convergence rate. As a result, control systems making use of the filtered-x LMS algorithm can perform poorly when the noise changes abruptly, such as when the vehicle changes gear.

This problem has, to some extent, been addressed by using pre-compiled feed-forward control systems, such as those described in US patent specifications 4,506,380, 5,692,052 and 5,758,311. Such control systems do not suffer from slow convergence, however the pre-compiled nature of the controller limits the adaptability of the controller.

Accordingly, there exists a need for an adaptive controller having a reasonable convergence rate.

In addition, field trials of noise cancellation systems have shown that operators of heavy mining equipment have individual preferences regarding the level of noise attenuation at certain frequencies. Some drivers use the sound of the engine as

part of their sensory input in controlling the vehicle. Accordingly, it would be desirable to provide a noise reduction system in which the level of attenuation can be adjusted or at least selected from a plurality of predefined configurations.

DISCLOSURE OF THE INVENTION

Throughout the specification, unless the context requires otherwise, the word "comprise" or variations such as "comprises" or "comprising", will be understood to imply the inclusion of a stated integer or group of integers but not the exclusion of any other integer or group of integers.

In accordance with a first aspect of this invention, there is provided a noise reduction apparatus for an enclosure, comprising:

error sensor means arranged to generate an error signal;

control means responsive to a reference signal to produce a control signal;

a transducer responsive to the control signal;

the control means comprising:

a first controller responsive to the reference signal to produce the control signal for the transducer,

a plant model responsive to the reference signal to produce a signal input to a second controller,

signal generation means for producing a further error signal from the output of the second controller, the output of the first controller and the error signal, and

adaptive means responsive to the further error signal to adjust the parameters of the first and second controllers simultaneously.

Preferably, the apparatus further comprises shaping filter means provided between the signal generation means and the adaptive means and arranged to process the further error signal and produce a processed further error signal input to the adaptive means.

Preferably, the apparatus further comprises reference sensor means and reference signal conditioning means responsive to the reference sensor means to produce the reference signal therefrom.

Preferably, the error sensor means is provided adjacent to an operator's head in use.

Preferably, the error sensor means comprises two microphones, one provided adjacent each ear of the operator.

Preferably, the apparatus further comprises a plurality of transducers and the control means comprises a plurality of controllers each of which is associated with one of the transducers, each controllers producing a control signal for the associated transducer.

Preferably, at least one of said controllers comprises a feedforward control channel.

Preferably, at least one said controllers comprises a feedback control channel.

Preferably, the reference signal for each feedback controller comprises a further signal produced by the signal generation means.

Preferably, the transducers comprise audio transducers and/or vibration transducers.

Preferably, the apparatus further comprises monitoring means arranged to monitor the noise level in the enclosure and disable the control means if the noise exceeds a predetermined threshold.

Preferably, said monitoring means resets the parameters of the controllers prior to enabling the control means.

In accordance with a second aspect of this invention, there is provided a noise reduction apparatus for an enclosure, comprising:

error sensor means arranged to generate an error signal;

control means responsive to a reference signal to produce a control signal;

a transducer responsive to the control signal;

the control means comprising:

a first controller responsive to the reference signal to produce the control signal for the transducer,

shaping filter means responsive to a user's selection, provided between the signal generation means and the adaptive means and arranged to process the error signal and produce a processed further error signal input to the adaptive means,

adaptive means responsive to the processed error signal to adjust the parameters of the first controller.

Preferably, said control means further comprises a plant model responsive to the reference signal to produce a signal input to a second controller, signal generation means provided before the shaping filter means for producing a further error signal from the output of the second controller, the output of the first controller and the error signal, the further error signal being input to the shaping filter means.

Preferably, the apparatus further comprises reference sensor means and reference signal conditioning means responsive to the reference sensor means to produce the reference signal therefrom.

Preferably, the error sensor means is provided adjacent to an operator's head in use.

Preferably, the error sensor means comprises two microphones, one provided adjacent each ear of the operator.

Preferably, the apparatus further comprises a plurality of transducers and the control means comprises a plurality of channels each of which is associated with one of the transducers, each channel producing a control signal for the associated transducer.

Preferably, at least one channel of the control means comprises a feedforward control channel.

Preferably, at least one channel of the control means comprises a feedback control channel.

Preferably, the reference signal for each feedback control channel comprises a further signal produced by the signal generation means.

Preferably, the transducers comprise audio transducers and/or vibration transducers.

Preferably, the apparatus further comprises monitoring means arranged to monitor the noise level in the enclosure and disable the control means if the noise exceeds a predetermined threshold.

Preferably, said monitoring means resets the parameters of the first and second controller prior to enabling the control means.

BRIEF DESCRIPTION OF THE DRAWINGS

Figures 1a and 1b are side and front views, respectively, of a vehicle cabin incorporating the noise reduction apparatus according to the preferred embodiment of the invention;

Figure 2 is a block diagram of a feedforward control circuit of the embodiment;

Figure 3 is a block diagram of a feedback control circuit of the embodiment; and

Figure 4 is a block diagram of a reference signal conditioning circuit of the embodiment.

BEST MODE(S) FOR CARRYING OUT THE INVENTION

The embodiment relates to a noise reduction apparatus denoted generally at 10 provided in a cabin 12 of a heavy mining vehicle or a marine vessel. However, it should be appreciated that the invention can be applied to control noise in other forms of enclosures, and that such enclosures need not be fully enclosed.

The noise in the cabin 12 of such a vehicle is often the product of several noise sources, such as the engine, the exhaust/muffler system and auxiliary equipment such as hydraulics, compressors, air conditioning units and fans, as well as noise sources external to the vehicle. Each of these noise sources can produce noise in the cabin 12 either by transmission of sound into the cabin 12, or by causing vibrations in the structure of the cabin 12, which in turn creates noise within the cabin 12. The embodiment uses a controller having a two channel feedforward circuit and a single channel feedback circuit.

In the embodiment, the cabin 12 includes a floor panel 14, a seat 16 attached to the floor 14 and a ceiling panel 18.

The noise reduction apparatus 10 of the embodiment comprises two reference sensors 20a and 20b, three error sensors 22a, 22b and 22c, a controller 24 and three transducers 26a, 26b and 26c.

The reference sensor 20a comprises a vibration sensor and is provided adjacent the vehicle's engine 28. The reference sensor 20b comprises a microphone provided near the vehicle's muffler 30.

The error sensors 22a and 22b each comprise a microphone provided above the seat 16. The error sensors 22a and 22b are provided spaced apart at opposite sides of the seat 16 such that in use, the operator's head would be received between the error sensors 22a and 22b. The error sensors 22a and 22b are connected to the controller 24.

The error sensor 22c comprises a vibration sensor that is provided on the floor panel 14 of the cabin 12. The error sensor 22c is connected to the controller 24.

In the embodiment, the controller 24 comprises a 2 channel feedforward circuit 24a, a single channel feedback circuit 24b and a reference signal conditioning circuit 24c. The reference signal conditioning circuit 24c forms a reference signal from information received from the reference sensors 20a and 20b.

The error sensors 22a and 22b each provide an error signal to one channel of the feedforward circuit 24a of the controller 24. The error sensor 22c provides an error signal to the feedback control circuit 24b.

The transducers 26a and 26b comprise audio transducers such as loud speaker drivers. The transducers 26a and 26b are attached to the ceiling panel 18 of the cabin 12 and are positioned generally above the corresponding error sensor 22a and 22b, respectively. In other embodiments, the transducers may be provided at other locations, depending upon the installation requirements and the available space in the cabin or other enclosure.

The transducer 26c comprises a vibration transducer attached to the floor panel 14. The error sensor 22c and the transducer 26c are provided on opposite sides of the floor panel 14 so as to be co-located one above the other. The transducer 26c may be in the form of a piezoelectric transducer or a magnetostrictive actuator. It is preferred that if used, the piezoelectric transducer is placed at a node of vibrations in the floor panel 14, whilst a magnetostrictive actuator is provided at an antinode of vibrations in the floor panel 14. Again, on other embodiments, vibrational transducers may be provided in other locations depending on installation requirements.

Each of the transducers 26a, 26b and 26c are connected to the controller 24 and receive control signals therefrom. The transducers 26a and 26b each receive a control signal from one channel of the feedforward control circuit 24a, and the transducer 26c receives a control signal from the feedback control circuit 24b.

Figure 2 shows a block diagram of the feedforward control circuit 24a. The feedforward control circuit 24a is responsive to a reference signal 32 produced by the reference signal conditioning circuit 24c, described below, from the signals received from the reference sensors 20a and 20b. The purpose of the reference signal conditioning circuit 24c is to increase the correlation between the reference signal 32 and the noise (shown in figure 3 at 34) in the cabin 12, improve the signal to noise ratio and adjust the relative balance between the signals received from the reference sensors 20a and 20b.

A plant 36 is shown in figure 2, representing the electro-acoustic system corresponding to the transducers 26a and 26b and the acoustic path between said transducers and the region about the user's head, where noise reduction is desired.

The feedforward control circuit 24a includes a first control system 38, an adaptive LMS system 40 and a shaping filter 42.

The first control system 38 receives the reference signal 32 and, based on its current parameters, produces a control signal shown at 44. The control signal 44 is sent to the transducer which forms part of the plant 36. In the embodiment, two feedforward control circuits 24a are used to produce two control signals 44, one for each of the transducers 26a and 26b. Each of the feedforward control circuits 24a use the same reference signal 32 produced by the reference signal conditioning circuit 24c.

The error signal, shown at 46, produced by each of the error sensors 22a and 22b is the sum of the noise 34 and the response of the plant 36 to the control signal 44. In the embodiment, the error sensor 22a produces an error signal for one of the channels of the feedforward control circuit 24a and the error sensor 22b

produces an error signal for the other channel of the feedforward control circuit 24a.

Existing feed-forward controllers would pass the error signal 46 into an adaptive LMS system along with the reference signal 32 so that the adaptive LMS system can update the parameters of the first control system 38. However, this would require the adaptive LMS system to be a filtered-x LMS system, which has a slow convergence.

To avoid this problem, the feedforward control circuit 24a includes a plant model 48, a second control system 50 and a signal generating means 52. The reference signal 32 is input to the plant model 48, and the output of the plant model 48 is input to the second control system 50 and the adaptive LMS system 40. The output of the second control system 50 is input to the signal generating means 52. The error signal 46 is also input to the signal generating means 52. The signal generating means 52 includes a further plant model 48 which takes as an input the control signal 44. The output of the further plant model 48 is subtracted from the error signal 46 to arrive at a model of the noise 34 shown at 54 in Figure 2. The model of the noise 54 is then combined with the output of the controller 50 to produce a second error signal at 56. Advantageously, the second error signal 56 allows the adaptive LMS system 40 to use traditional LMS convergence rates rather than the slow filtered-x convergence rate.

The second error signal 56 is input to the shaping filter 42. The shaping filter 42 forms a filtered error signal which is input to the adaptive LMS system 40. The adaptive LMS system 40 then makes adjustments to the operational parameters of the first and second control systems 38 and 50 in order to minimise the filtered error signal input to the adaptive LMS system 40. The same changes are made to the parameters of both the control systems 38 and 50, such that the first and second controllers 38 and 50 have the same parameters.

The shaping filter 42 modifies the second error signal 56 prior to input to the adaptive LMS system 40. This provides two advantages. First, a user can customise the noise reduction achieved at certain frequency ranges according to

his or her preferences. Since the adaptive LMS system 40 attempts to minimise the signal appearing at its input from the output of the shaping filter 42, any portions of the second error signal 56 that are filtered or attenuated by the shaping filter 42 will not be attenuated to a significant degree by the controller 24. Depending upon the implementation adopted, the shaping filter 42 can offer customisable shaping or provide a plurality of predetermined shaping filters from which a user can select one. Secondly, the shaping filter 42 can be used to adjust the sensitivity of the controller 24 at certain frequency ranges. Since the gain-bandwidth product of a control system is finite, reducing the bandwidth over which the controller must work in effect increases the amount of attenuation delivered to the remaining frequencies. This is particularly advantageous if the anticipated noise spectra of the cabin 12 is known. These two effects can be used in combination to allow design-level control of the operating frequency ranges, within which a user can adjust the noise reduction achieved at certain frequency ranges according to his or her preferences

Figure 3 shows a block diagram of the feedback control circuit 24b. Like reference numerals are used in relation to figure 3 as were used in figure 2. The feedback control circuit 24b shown in figure 3 differs from that shown in figure 2 in that a model noise signal 54 is used to replace the reference signal 32 by feeding the signal 54 back to the input of the first control system 38 and plant model 48. The feedforward control circuit 24b shown in figure 3 is used to control the transducer 26c.

Although not shown in the drawings, the noise reduction system 10 also includes a monitoring circuit that monitors the control signal 44. If the control signal 44 exceeds a predetermined threshold criteria, the controllers 50 and 38 are deactivated by the monitor circuit. This is to prevent noise within the cabin 12 reaching excessive levels if the controller 24 malfunctions and increases rather than decreases the noise within the cabin 12. The monitoring circuit also resets the parameters within the first and second controllers 38 and 50 back to an initial condition, following which the control systems 38 and 50 are enabled.

Figure 4 shows a block diagram of the reference signal conditioning circuit 24c. The reference signal conditioning circuit 24c comprises two bandpass filters 60a and 60b, two phase locked loops (PLLs) 62a and 62b, two phase compensators 64a and 64b, a summer 66 and a buffer 68.

The bandpass filter 60a, the PLL 62a, and the phase compensator 64a are connected in series, with the bandpass filter 60a being responsive to the signal received from the reference sensor 20a. The output from the phase compensator 64a is connected to an input of the summer 66.

The bandpass filter 60b, the PLL 62b, and the phase compensator 64b are connected in series, with the bandpass filter 60b being responsive to the signal received from the reference sensor 20b. The output from the phase compensator 64b is connected to another input of the summer 66.

The bandpass filters 60a and 60b define the selectivity of the controller 24 and are used to remove unwanted frequency components present in the signals from the reference sensors 20a and 20b, respectively.

The PLLs 62a and 62b lock onto a frequency component of the filtered signals from the bandpass filters 60a and 60b. The PLLs 62a and 62b have a limited frequency band of operation to prevent them from tracking other components in the filtered signals. The bandwidth of operation of the PLLs 62a and 62b is selected based on the expected rate of change of the noise sources. For example, if the engine changes gear over the course of 500ms, a bandwidth of 2Hz is chosen for the PLLs 62a and 62b. Each of PLLs 62a and 62b produce a constant-amplitude output from its voltage controlled oscillator (not shown).

The output of each PLL 62a, 62b is input to a corresponding phase compensator 64a and 64b. The phase compensators 64a and 64b provide adjustment of the relative phase between the signals output from the PLLs 62a and 62b.

The summer 66 adds the signals received from the phase compensators 64a and 64b. The buffer 68 provides gain trimming for the summed signal. The output of the buffer 68 forms the reference signal 32.

It should be appreciated that this invention is not limited to the particular embodiment described above.

For example, although the embodiment is described as having a two channel feed-forward control circuit and a single channel feedback control circuit, other embodiments may use only one form of control circuit or may utilise any number of channels as needed.

It should be noted that the reference sensors can take any appropriate form. In particular, in relation to the engine 28 it may be possible to utilise an indication of the speed of the engine from the tachometer or an audible signal derived from the engine bay rather than a vibration signal.